A new evaluation method of surface finish of composite automobile panels using waveform analysis

Hu S., Hoa S.V.and Ganesan R.

Concordia Center of Composites
Department of Mechanical and Industrial Engineering
Concordia University
Montreal, Quebec, H3G 1M8, Canada
Center for Research in Polymers and Composites (CREPEC)
hoasuon@alcor.concordia.ca

Key Words: cross correlation coefficient, class A surface finish, similarity, spectrum, filter, composite panel

Abstract: *The surface finish of composite plates made using Resin Transfer Molding of glass/polyester was studied. The objective was to develop an objective method (rather than using human judgement) to differentiate the quality of one surface from another. Initially commonly used current techniques are utilized to assess the quality of the surface finish. These include subjective evaluation through a survey of observations from a group of people; the use of the average amplitude of the signals; frequency analysis and filtering. For surfaces that have approximate quality, human visual observation can differentiate the quality between the surfaces, but the objective methods (average amplitude, frequency spectrum, and filtering) can not. A new objective technique was found to be able to distinguish surfaces of approximate quality. This uses the comparison between the parameters of a reference good surface to those of the surface under consideration. A comparative index can be obtained to indicate the degree of similarity between the surface under study and the reference (good) surface.*

1. Introduction

Recently there has been increasing interest to use composites to make automotive components, particularly automotive panels [1-3]. For these applications, the surface finish of the exterior surface of the composite panels is of critical importance to obtain customer acceptance. For low cost operation, Resin Transfer Molding is believed to be a good method for the manufacturing of these composites panels [4-7]. Current technique using subjective evaluation does produce results that meet with customer satisfaction [8]. However, subjective evaluation is cumbersome and is statistically dependent. A large number of people are required to provide meaningful results. This may not facilitate automation. As such objective techniques that can provide the same result as subjective evaluation would be desirable. In this work, many commonly used current objective methods were used to evaluate the surface qualities of composite panels made by the Resin Transfer Molding process. The results are far from the subjective evaluation. A few new approaches have been attempted. Out of these, one technique was found to be able to provide the objective evaluation that is comparable to the subjective evaluation.

The challenge of the project came from Ford Motor company, as part of the AUTO 21Network of Centers of Excellence program. The challenge is to find an objective method that can distinguish composite panel surfaces of approximate quality.

2. The proposed problem

Seven panels were supplied for the project. Ford Motor company provided the steel panel and two composite panels made by Resin Transfer Molding (2a and 2b). Four other composite panels (made by Resin Transfer Molding) were supplied by McGill University. These are listed in Table 1.

Table 1: Plates supplied for the project

Panel label	Material	Comment
Steel	Steel	Supplied from Ford
2a	Composite made by RTM	Ford, No LPA
2b	Composite made by RTM	Ford, with LPA
JU29	Composite made by RTM	McGill, with LPA
JL01	Composite made by RTM	McGill, with LPA
JL13	Composite made by RTM	McGill, with LPA
JL15	Composite made by RTM	McGill, with LPA

The steel plate has a painted surface. It looks very smooth. Panel 2a was made without the use of Low Profile Additive (LPA) while panel 2b was made with Low Profile Additive. The other four composite panels were made using Resin Transfer Molding at McGill University. Figure 1a shows low magnification photographs of the surfaces of the steel panel and Figure 1b shows the photographs of the six composite panels.

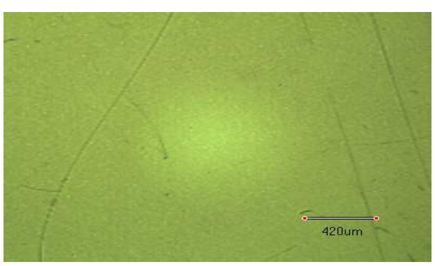


Fig.1a: Surface of steel plate

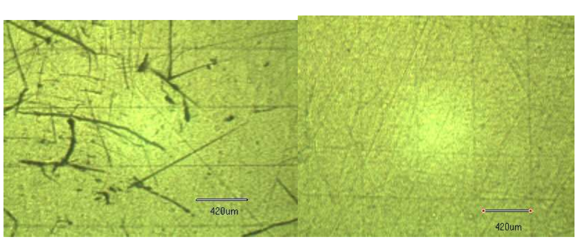
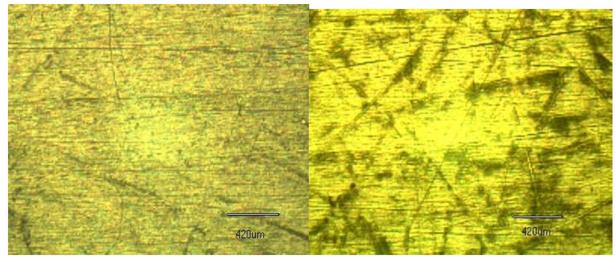
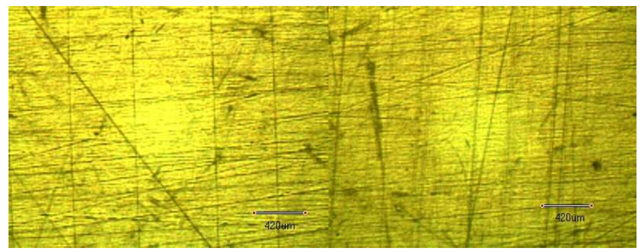


Plate 2a Plate 2b



JU29 panel **JL01 panel**



JL13 panel **JL15 panel**

Fig. 1b: Surface appearance of the six composite panels

The problem posed was how to differentiate the quality of the surfaces of these panels using objective measurement techniques. Subjective evaluation of the surfaces using visual observation may indicate which surface is better (more pleasing to the eyes like class A finish) but which quantitative measure that can differentiate the surfaces is the subject under investigation. It should be noted that to be pleasing to the eyes (class A finish) may need a combination of parameters including roughness, waviness, frequency spectrum etc.

3. Evaluation of quality of the surfaces of the panels

3.1 Evaluation of surface quality using commonly used current techniques:

3.1.1 Visual observation:

The most commonly used technique for the evaluation of surface quality is human visual observation. This has been used in industry as a most reliable method. To establish a reference this method is used here. A panel of 28 graduate students and research associates in the composites lab were asked to examine the surface of the panels and to give the ranking (1 is best quality and 7 is least quality). Table 2 shows the results of this survey.

Table 2: Average rank of surface quality levels of the seven panels by visual observation

	ST	2a	2b	JU29	JL01	JL13	JL15
Average values	1.035	5.39	1.96	3.42	6.57	4.78	4.78
Rank	1	6	2	3	7	4	4

3.1.2 Microstructure observation of cross sections and observation of surface using AFM:

The second technique used to determine the quality of the surface was done using optical microscope and AFM to observe cross sections and surface of the panels.

It is difficult to decipher the quality of the surface finish of the panels based on micrographs of the cross section and surface. This technique therefore was deemed not to be suitable for determination of surface quality.

3.1.3 Characterisation of surfaces using average amplitude of signals:

In practice, Ra value (average absolute amplitude) is a main parameter which is most widely used to describe surface roughness. At present in research works Ra is still used as the parameter for the characterisation of the surface of composite plate [9, 10]. Table 3 shows the summary of average Ra of the panels and shows the ranking of the plates based on average Ra values.

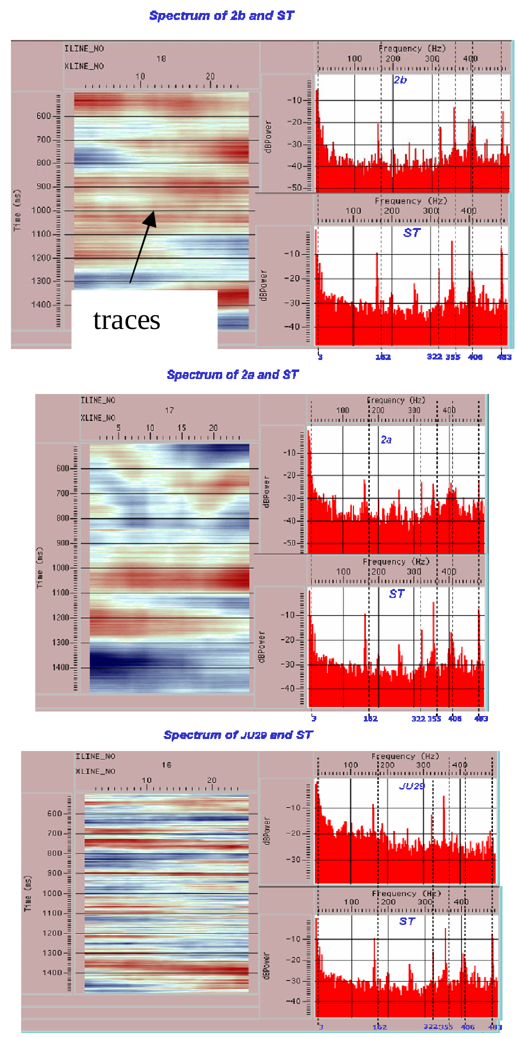
Table 3: Average Ra values and rank of composite plates and painted steel plate

Name	2a	2b	JU29	JL01	JL13	JL15	ST
Ra(μm)	0.220	0.195	0.143	0.149	0.132	0.143	0.078
Rank	6	5	3	4	2	3	1

3.1.4 Characterisation of surfaces using Frequency spectrum analysis and filtering:

Fourier analyses are used to decompose a time series into a suite of waveforms [11, 12]. Characteristic peak amplitude for the frequency could show surface character of the material. Also by filtering, characteristic curves of the surface at different frequency ranges can be shown. This may reveal the surface shapes of the material in different wave lengths. By DFT (Discrete Fourier Transform) analysis [13. 14], surface characteristics of materials in frequency domain can be determined. Dominant frequency series and filtering analysis show that low frequency components would contribute to surface shapes of the plate and high frequency components would be related to the surface brightness.

a) Fourier analysis of Surface profiles of panels [15]
Fig. 2 shows spectra of the seven panels, each panel has 25 traces, as calculated by DFT.



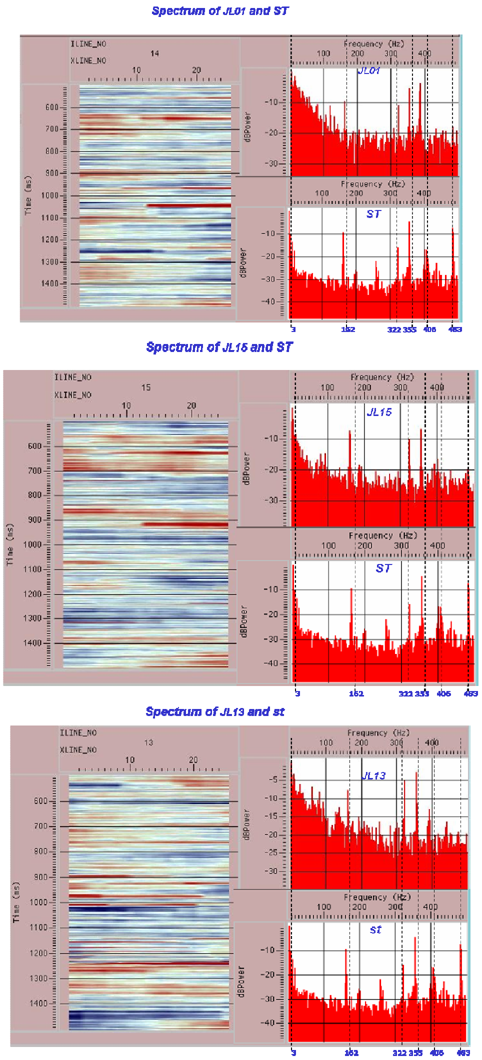


Fig. 2: Frequencies and spectra of seven panels

It can be seen from Fig. 8 that painted steel plate has characteristic peaks at 160Hz, 322Hz, 355 Hz, 406Hz and 483Hz, respectively. Since the steel plate has good surface finish and if this is assumed to be of class A finish, the characteristic peaks of this panel may be used as a reference. Spectrum analysis shows composite plate 2b has the most similar spectrum to the spectrum of painted steel plate in the six composite plates. Table 4 shows the ranking of the surface of the panels based on frequency spectrum. The matching is not definite and it is difficult to determine surface quality levels by frequency spectrum.

Table 4: Rank of surface quality levels of the six panels by spectrum analysis

	ST	2a	2b	JU29	JL01	JL13	JL15
Rank		2	1	2	2	2	2

b) Filtering analysis [16]

By filtering, characteristic curves of the surface at frequency range can be shown. Low frequency means large wavelength. Therefore, curves of amplitudes and displacement at low frequencies would give the surface shape of the plate. The curves of amplitude and displacement at high frequencies would reflect surface brightness of plates because the resolution of human eyes is around 0.15mm. Filtering analysis is helpful to understand the characteristics of panels.

In the PostStack software Ormsby filter is used. Based on analysis of characteristic peaks, low frequency and high frequency analyses are performed in order to understand surface properties. In low frequency window 3-5Hz and high frequency window 355-357 Hz, the curves of characteristic amplitudes of the surfaces of the seven panels can be obtained and shown in Fig. 3 and Fig. 4

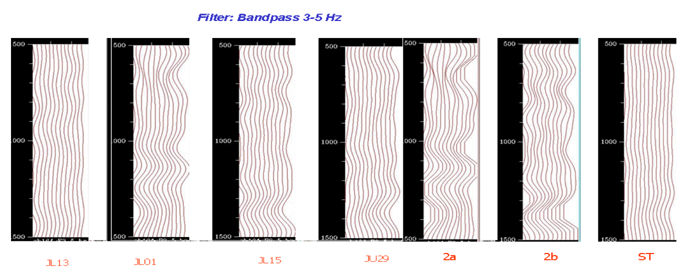


Fig. 3: The surface shapes of the seven plates for filtering in bandpass 3-5 Hz

It is seen from Fig. 3 that painted steel plate has the best flatness. Composite plates JL13 and JU29 have also better flatness. Composite plates 2b, 2a, JL15 and JL01 have bigger waviness in low frequency. General speaking, the waviness of samples from Ford are larger than that of samples from McGill University.

Results of filtering in bandpass 355-357 Hz are shown in Fig. 4. It is seen from these results that surface amplitudes of the panels all have more uniform distributions, which is more pleasing to the eyes. However, painted steel plate has higher characteristic frequencies. The surface of painted steel pate has the highest brightness.

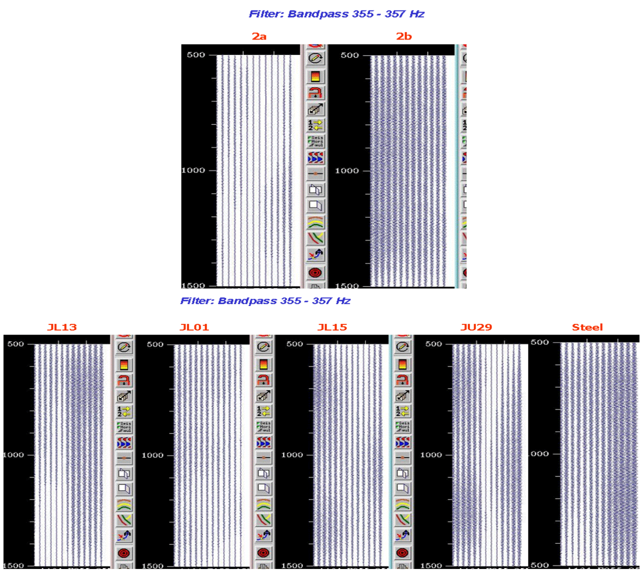


Fig. 4: Surface shapes of the seven plates for filtering in bandpass 355-3575 Hz

Table 5: Rank of surface quality levels of the seven panels by filtering analysis

	ST	2a	2b	JU29	JL01	JL13	JL15
Rank	1	6	5	3	4	2	3

Comparing the ranking in Table 5 and that of Table 2, it can be seen that the filtering analysis ranking does not agree with that made by visual observation.

The results from the ranking of the panels using currently used objective techniques (observation of cross sections using microscopes, AFM, Ra, frequency analysis and filtering) do not seem to be able to provide consisting evaluation of the surface quality as compared to visual observation of the surface. The lack of an objective technique to distinguish the quality of surface of composite panels plates calls for the need to develop new methods to treat the data. Some other quantitative method is essential to bring out the difference.

3.2 New approaches

3.2.1 Correlation and Similarity analyses:

Most if not all of the surface analysis techniques currently available present the surface parameters in absolute scale. This means that the surface parameters such as Ra and its treated values present the characteristics of the surface on it own. An observer has to judge from the appearance of the surface to see if that surface has good quality. This technique may work well in a qualitative sense but not well in a quantitative sense. The important aspect for a quantitative determination of a surface quality may not be the absolute parameters of the surface. It may be easier to provide a quantitative measure of a surface by comparing the parameters of that surface to those of a reference surface. The basis of analysis will be based on the similarity or difference between the parameters of the two surfaces. This approach is very important because in engineering many problems are, and should be, analyzed on the basis of comparison between objects.

We now apply this principle and assume that the painted steel plate can be used as the standard surface. Comparison is then made between the parameters for the surface of composite panels 2a, 2b, JU29, JUL01, JUL13 and JUL15 with those of the painted steel surface. Judging by the difference between the parameters of the two pairs of surface, we may be able to distinguish the quality of the surfaces of the composite panels.

In this paper, the analysis of surface quality of composite plates is conducted by using PostStack software[17]. The software used for the measurement system is Surfpark. The software has 4 standards. They are Oldmix, JIS1994, ISO 1997 and ANSI1995. Each standard has a few definitions for the surface parameters such as Ra, and so on. Oldmix standard is used. The cut-off wavelength used is 2.5 mm. The data used for analysis is processed by LandMark system. The acquisition data from Surpark are converted and inputted to LandMark software system. Comparison is made between the parameters of the composite panels and those of the painted steel surface.

Treatment of data before comparison:

Figure 5 shows the appearance of the ensemble of 25 scans along the length of the scans for the surfaces of the seven panels.

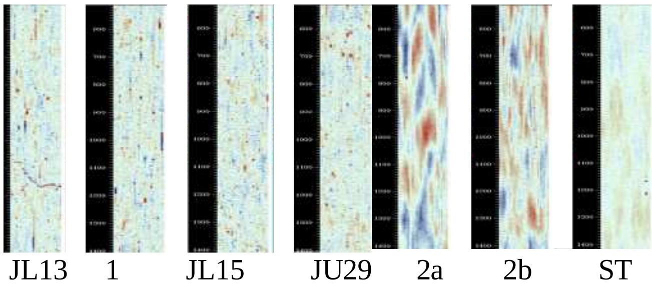


Fig. 5: Pictures of original amplitudes of composite and painted steel plate

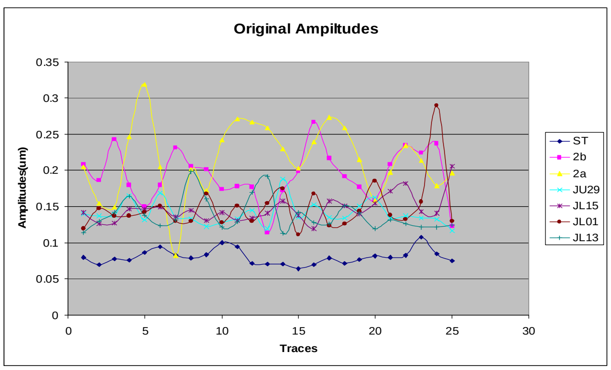


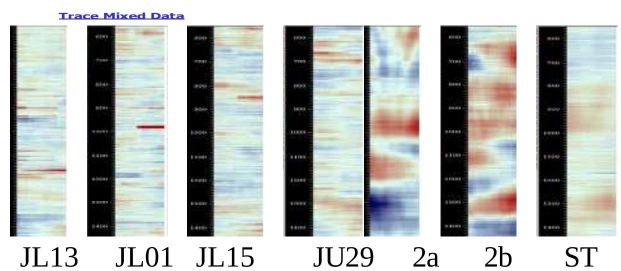
Fig. 6: Original amplitudes of seven panels

The color pattern shows the variation in the amplitude of the signals (i.e. darker color means large amplitude variation). From Figure 5, it can be seen that the steel plate has least amplitude variation. Comparison of the variation of the average Ra for the seven plates was shown in Figure 6. The amplitudes vary significantly. To reduce the variation from trace to trace, the input data was processed with Trace Mix procedure. This is explained as follows:

Trace mix treatment:
Trace mix is a method used to reduce the variation from trace to trace [18, 19]. The input data can be processed with trace mix. For each trace in the mix, the value at a given sample location is multiplied by a weighting factor. All the weighted values are then added, and this sum is assigned as the sample value for the central trace. The "rolling" filter then moves forward one trace, and the process is repeated. At the edges of the data, when the specified number of traces for mixing is not available, the filter uses the available traces to "roll-on" and "roll-off."

This weighted trace mix is designed to reduce the variation from trace to trace, thus producing a smoother looking section and enhancing the continuity of material. It is smooth treatment for measurement data. On average, smoothed profile of the surface of the material reflects the surface characters of this material. The sum of the weighting factors is always 1. So if one chooses equal weighting for a trace mix of three traces, the samples from each trace will be multiplied by 0.333.

This weighted trace mix is designed to reduce the variation from trace to trace, thus producing a smoother looking section and enhancing the continuity of material. It is a smoothing treatment for measurement data. Figure 6 show pictures of the smoothed data and their amplitudes.



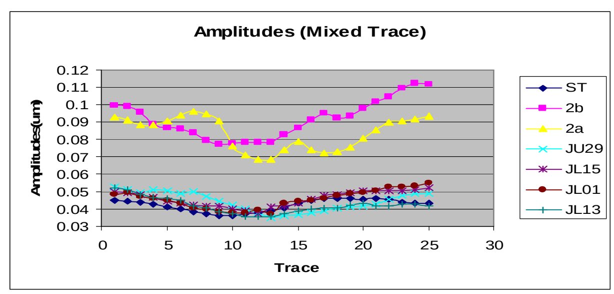


Fig. 6: **Pictures of mixed traces for the seven panels**

It can be seen from Fig. 6 that these data are smoothed and have less variations. This smoothed surface may reflect better the character of the surface.

3.2.2.1 Correlation analysis

This is used to determine the similarity between reference trace and target trace. A value of 0.0 indicates that the two traces are completely uncorrelated. A value of 1.0 indicates identical traces.

Fig.7 is a model which is presented as in 3 dimensions. One coordinate represents materials, the other represents traces, and the third one is associated with samples. In this way, cross correlations between painted steel plate and composite plates can be calculated by equation (1) [20].

.

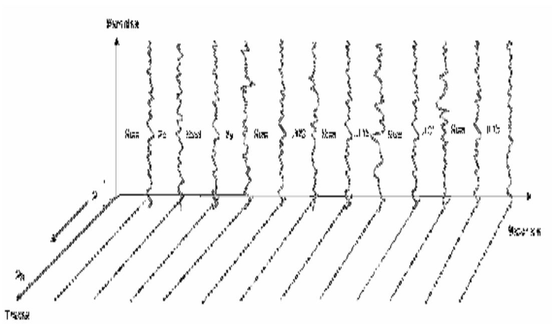


Fig. 7: Cross-correlation analysis of painted steel plate, and composite plates

$$\gamma_{12} = \frac{E\{[X_1 - E(X_1)][X_2 - E(X_2)]\}}{\sqrt{D(X_1)}\sqrt{D(X_2)}} = \frac{C_{12}}{\sqrt{C_{11}}\sqrt{C_{22}}} \qquad (1)$$

Where γ_{12} is coefficient of cross correlation for random variables X_1 and X_2. E(X) is mathematical expectation that can be expressed as follows:

$$E(X) = \lim_{N\to\infty} \frac{1}{N}\sum_{i}^{N} x(t_i) = \int x(t)p(x,t)dx \qquad (2)$$

where, p(x, t) is probability density function. D(X) represents variance that can be expressed as follows:

$$D(X)=E[(x(t)-E(X))^2]$$

$$= \int (x(t) - E(X))^2 p(x,t)dx \qquad (3)$$

C_{12} represents covariance for X_1 and X_2. It can be written as:

$$C_{12} = E\{[X_1 - E(X_1)][X_2 - E(X_2)]\} \qquad (4)$$

For the case under study,

$$\gamma_{ik} = \frac{E\{[X_i - E(X_i)][X_k - E(X_k)]\}}{\sqrt{D(X_i)}\sqrt{D(X_k)}} = \frac{C_{ik}}{\sqrt{C_{ii}}\sqrt{C_{kk}}}$$

i, k=1,2,3….25. (9)

Fig. 8 shows the coefficients of cross correlation between painted steel plate and composite plates. In this model trace of painted steel plate is reference trace, target traces are that of composite plates.

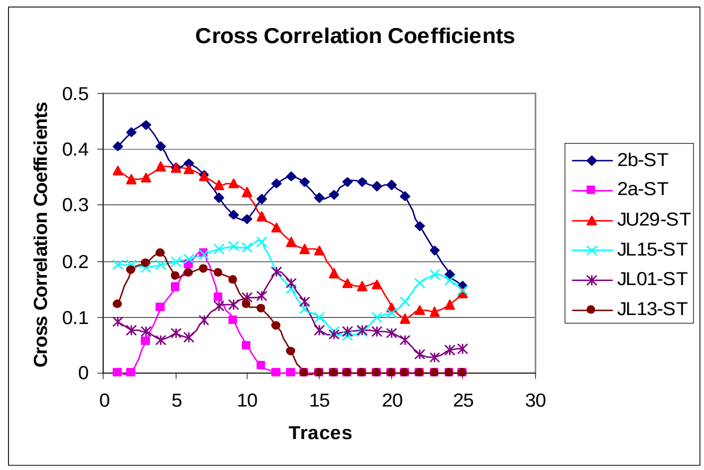


Fig. 8: Cross-correlation between combinations of steel-2a and steel-2b etc.

The results calculated show composite plate 2b and painted steel plate have the best correlation coefficients in all materials. Sample JU29 has the next best correlation with painted steel plate. Table 6 shows average values of cross correlation coefficients and the ranking for the six composite plates.

Table 6: Average cross correlation coefficients

	2a-ST	2b-ST	JN29-STl	JL01-ST	JL13-ST	JL15-ST
Correlation coefficients	0.041	0.325	0.240	0.087	0.078	0.162
Rank	6	1	2	4	5	3

Though Ra values of 2b is a little higher than those of samples from McGill University, its extent of surface correlation with painted steel plate is greatest. This is because its waveforms are more similar to that of painted steel plate. The second one in rank is sample JU29. Surface correlation of sample 2a with painted steel plate is lowest. However, even for composite plate 2b, its average correlation extent with painted steel plate is only round 33%. This means surface quality level of composite plates still is far away from surface quality level of painted steel plate.

3.2.2.2 Similarity analysis [17, 21]

Distance coefficient is an important method to describe similarity between objects. It is easy to see how distance between two points can be used to measure similarity. Zero distance between two points clearly means that there are no numerical differences between two objects; they are completely similar. Greater distances correspond to lesser similarity, so distance measures are often called dissimilarity, rather than similarity coefficients.

In this model assume that the surface of the painted steel plate has class A surface finish. Therefore, it is used as a reference surface. Surface profiles of composite plates can be compared with the reference surface profile. In this way, it may be possible to distinguish surface quality between composite plates and can describe the extent of similarity between composite plates and painted steel plate with class A surface finish.

Manhattan Distance

Manhattan distance or City Block is an efficient statistical measurement of similarity/dissimilarity. For this situation, Manhattan distance uses two equal length wavelets with N time samples and sums the absolute value of the difference in corresponding samples for all samples. Manhattan distance is given by:

$$M = \sum_{i=1}^{N} |A_i - B_i|$$

where: M is the Manhattan distance;A is the reference wavelet; B is the target wavelet guided by the horizon; N is the number of discretizations in each wavelet. Two identical wavelets will result in a Manhattan distance value of 0 and wavelets that are not identical will result in a positive Manhattan distance.

In PostStack software the center trace window is compared to the target trace window using Manhattan distance (shown in Fig. 9).

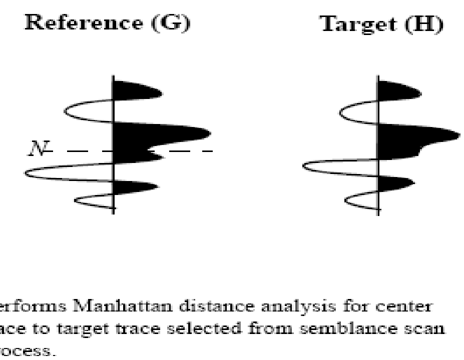


Fig. 4.9: A schematic diagram for similarity by Manhattan distance

The center trace is a reference function. Manhattan distance is the sum of the absolute value of the sample differences between the windows. This sum (numerator) is divided by the sum of the absolute values of each sample of the two traces within the specified window. The resulting values are numbered between 0 and +1. Number 0 expresses that the two trace are total similarity. It can be expressed as equation (10).

$$M_d = 100 \frac{\sum_{K=N-n/2}^{K=N+n/2} |G_k - H_{k+d}|}{\sum_{K=N-n/2}^{K=N+n/2} (|G_k| + |H_{k+d}|)} \qquad (10)$$

Where M_d is Manhattan distance for any pair of traces, G and H, n is the number of digitizations in the wavelet, d is the integer sample shift, N is the center sample of the reference trace, 100 is scalar to facilitate display, G_k is Reference wavelet at k, H_k is Target wavelet at k.

In the PostStack program d is integer sample shift which would give a better match for the two traces. PostStack would search for a possible d automatically. For minimum similarity, the minimum value will be output.

Minimum similarity is used to calculate semblance values. Fig. 10 is results of semblance values that were calculated for painted steel & for samples 2a, 2b, JU29, JL01, JL13 and JL15 respectively. It can be seen from Fig. 10 that surface profiles of 2b are more similar to those of painted steel plate than that of 2a. However, similarity extents of surface profiles of composite plates with the painted steel plates are very low. Average semblance values are between 54 and 70 for plate 2b (Note that the lower is the semblance value, the better is the similarity between the surfaces of 2b to that of steel). This means there is a big gap between surface qualities of composite plates and painted steel plate.

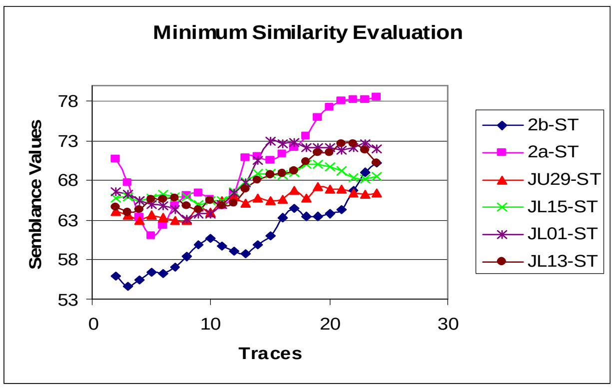


Fig. 10: The minimum similarity calculation for the seven panels

(The higher value indicates the higher dissimilarity.)

Table 7 shows average semblance values of the six panels.

Table 7: Average Semblance values (minimum similarity) of the six panels

	2a-ST	2b-ST	JU29-ST	JL01-ST	JL13-ST	JL15-ST
Semblance values	70.2	60.9	65.1	68.5	67.7	67.4
Rank	5	1	2	4	3	3

Sample JL01 and 2a have low similarity to surface of painted steel plate in the panels. JL13 and JL15 have almost same similarity to painted steel plate.

This type of analysis method describes similarity between objects. It not only considers surface waveforms, but also considers amplitudes of waveforms. It can be seen from Table 7 that plate JL13 is a little better than plate JL01, which may be because the amplitudes of plate LJ13 are lower than that of plate JL01.

4. COMPARISON OF CALCULATION RESULTS WITH VISUAL OBSERVATION

A summary of ranking results from Tables 2, 3, 4, 5 and 6 are shown in Table 8.

Table 8: Summary of ranking results from all methods

	ST	2b	JU29	JL13	JL15	2a	JL01
Visual Observation	(Ref.) (1.035	1 (1.96)	2 (3.43)	3 (4.79)	3 (4.79)	4 (5.39)	5 (6.57)
Ra (µm)	(Ref.) 0.078	4	2	1	2	5	3
Spectrum	2	1	2	2	2	2	2
filtering	(Ref.)	4	2	1	2	5	3
Correlation	(Ref.)	1 (0.35)	2 (0.24)	4 (0.08)	3 (0.16)	5 (0.04	4 (0.09)
Similarity	(Ref.)	1 (60.9)	2 (65.1)	3 (67.7)	3 (67.4)	5 (70.2)	4 (68.5)

It can be seen from Table.11 that there are significant differences in the evaluation between visual observation and Ra, MEM, spectrum and filtering analysis. It can also be seen from Table 11 that results of calculation by similarity model are very close with evaluation results by 28 people except for sample 2a and JL01. For Samples JL13 and JL15 the ranks by visual observation gave are the same, i.e, by visual observation, they are of the same quality level. Results of calculation by similarity model also show that they have almost the same surface quality levels. Results of calculation by cross correlation model are almost identical with results by similarity model. The results of calculation seem to show the same quality level for sample JL01 and JL13. However, correlation coefficients describe similarity of waveforms, waveform of JL01 may be a little better that that of JL13. However, Ra value (0.132 µm) of JL13 is smaller than that (0.149 µm) of JL01. Therefore, when effects of amplitudes are considered, semblance values of JL13 in similarity model are a little better than that of JL01.The methods that agree most with visual observation are similarity and cross correlation methods.

5.Conclusion and recommendation of a new procedure

Conclusions

Visual observation shows that in most cases it is difficult to distinguish surface quality of composite plates only by Ra values.

The method of mixed trace is used as pre-processing of the data. The method can reduce random fluctuation of the data.

A new comparison analysis method is proposed: The surface finish with class A of painted steel plate is used as a reference surface and different surfaces of composite plates are compared to the reference surface. In this way, the differences between surface quality levels of composite plate can be distinguished.

A 3D model is proposed, in which 3 coordinates represent materials, samples and traces respectively. The model establishes relationships between the three parameters. On the basis of the model, mathematical methods can be used to analysize surface quality levels.

Through these mathematical methods, differences between the reference function and the target function can be found. By analysis of differences, surface quality levels between composite plates can be differentiated.

A 3 D cross correlation model and similarity model are proposed to analyze surface profiles between reference surface profiles and target surface profiles. The method can be used to discuss the surface similarity and similarity of waveforms between reference function and target functions.

On the basis of correlation and minimum similarity models, the surface profiles of six composite plates are compared to the reference function. Calculation results show that the calculating results of correlation and similarity agrees well with results from visual observation, in which minimum similarity analysis can match results of visual observation best.

Spectrum analysis and filtering analysis show that the steel plate has the best flatness and waviness of plates from Ford is greater than that of plates from McGill University.

Recommendation of new procedure for evaluation surface quality

For evaluation of surface quality of composite plate, a new procedure is suggested as follows:

• The surface of class A surface finish is defined as a reference surface.

• 3 D data volume is established, in which the relationship of materials, traces and samples is set up. The Data are processed by trace mix.

• Cross correlation and similarity analysis models can be used to calculate correlation coefficients and semblance values.

This presents a significant breakthrough in the evaluation of surface quality for components made using composite materials. This is because current techniques, while sophisticated, only present the information of the surface itself, and absolute values are usually given. The absolute quantities some time are very close together and as such they can not differentiate the surfaces, while visual observation can.

Acknowledgement : Financial support from the Natural Sciences and Engineering Research Council of Canada, Auto21, Ford Motor Company (U.S.) and material support from McGill University and the University of Calgary are appreciated

REFERENCES

[1] U.S. Department of Agriculture Forest Service, “Wood Handbook: Wood as an Engineering Material, Agricultural Handbook No. 72”, Washington, DC, 1987.

[2] “Introduction to Composites”, 4th Edition, Composites Institute, Society of the Plastics Industry, New York, NY, 1998.

[3] D. V. Rosato, “Designing with Reinforced Plastics”, Hanser / Gardner, Cincinnati, Ohio, 1997.

[4] C. F. Johnson, “Resin transfer molding”, Composite Materials Technology-Process and Properties, P. K.Mallick and S. Newman, ed., Hanser Publisher, New York, 1990.

[5] LR Thomas, AK Miller and AL Chan, “ Fabrication of Complex High Performance Composite Structures at Low Cost Using VARTM”, In: International SAMPE symposium and exhibition (proceedings), vol. 47 (II); 2002, pp 1317–29.

[6] S. G. Advani, E. M. Sozer, “Liquid Molding of Thermoset Composites”, In: Talreja R, Manson J-AE, editors. Polymer matrix composites.Editor in Chief Kelly A, Zweben C, Amsterdam, Elsevier ScienceLtd., 2001, pp. 807–44.
[7] L Ascani, “Recent Advancements and Technical Needs in Structural Concepts, Fabrication, and Joining Flight-Vehicle Materials, Structures, and Dynamics –Assessment and Future Directions”, vol. 1. New York, USA: ASME; 1994, pp. 67–171.
[8] J. Seefried, “SMC-Außenhautteile in Class-A,” Proceedings SMC Automotive, DaimlerChrysler Sindelfingen, 1998.
[9] M. Neitzel, M. Blinzier, K. Edelman and F. Hoecker, “Surface QualityCharacterization of Textile-Reinforced Thermoplastics”, Polymer Composites, Vol.21, No.4, Aug.2000, p. 630.
[10] Mandy L. Herring, “Surface Analysis for the Comparison of Quickstep and Autoclave Surface Finish”, School of Engineering and Technology, Deakin University, Australia, 2003.
[11] A. Papoulis and S. U. Pillai, “Probability, Random Variables, and Stochastic Processes”, The McGraw-Hill Companies, Inc, 2002.
[12] A.V. Oppenheim, R.W. Schafer, “Digital Signal Processing”, Prenti-Hall, Inc, 1975.
[13] G.B. Lockhart and B.M.G. Cheetham, “Basic digital signal processing”, Butterworths & Co. Ltd, 1989.
[14] S. W. Smith, "The Scientist and Engineer's Guide to Digital Signal Processing," California Technical Publishing, 1998.
[15] “SpecDecomp Used Guide”, Landmark Graphics Corporation, Houston, USA, 2003, p5-120
[16] PostStack Family Reference Manual, Landmark Graphics Corporation, Houston, USA, May 2002, pp33-36.
[17] “PostStack Family Reference Manual”, Landmark Graphics Corporation, Houston, USA, 2003, pp362-436.
[18] “PostStack Family Reference Manual”, Landmark Graphics Corporation, Houston, USA, May 2002, p.105.
[19] S. Hu, S.V. Hoa and R. Ganesan., “Evaluation of Surface Finish of Composite Automobile Panel”, The 21st Annual Technical Conference of the American Society for Composites, The University of Michigan, Dearborn Michigan, September17-20, 2006.
[20] Y. Zhou, “Introduction to Stochastic processes”, Beijing University of Aeronautics & Astronautics, 2000.
[21] A.R.H. Swan and Sandilands, “Introduction to Geological Data Analysis”, Blackwell Science Ltd, 1995.